A CONVENTIONAL SINGLE-PHASE FULL BRIDGE CURRENT SOURCE INVERTER WITH LOAD VARIATION

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Abstract: This paper presents a conventional single-phase full bridge current source inverter with load variation. Different operational modes of this inverter are depicted. A novel rectified sine-triangular wave pulse width modulation technique is applied. The firing signals of the each of the power switch are generated from comparing rectified sinusoidal wave as the reference with triangular wave as carrier signal. Waveform analysis has been detailed to obtain the harmonic amplitude of the output current. This paper reveals that conventional single phase current source inverter operates with different loads generates variable percentages of THD with constant modulation index of 0.8 and frequency modulation index of 40. The simulations have been done in MATLAB/SIMULINK to showcase the harmonic spectrum, output voltages and currents waveforms.

Keywords: Current source inverter, sine-triangular pulse width, harmonic amplitude, inverter, MATLAB simulation.

1. INTRODUCTION

This paper aims to extend the knowledge about the voltage source inverter to current source inverter topology. Generally, Inverters can be categorized into two types such as single phase inverters and three phase inverters. Inverters are also classified as voltage source inverters where the small or negligible reactor is connected in series with voltage supply and current source inverter where high inductance is connected in series with voltage supply. Due to continuous research on inverter topologies, consequently inverter can be subdivided into two namely; conventional inverters and multilevel inverters. Thus, conventional inverter has a maximum of two output voltage or current level. Due to this low voltage level, conventional inverters are associated with high output harmonic content with less number of power switches. On the other hand, multilevel inverter configuration has a minimum of three output voltage level with reduced harmonic content and increased number of switches.

Unlike voltage source inverter which are very common and in wide use due to merit accorded to them, conventional current source inverters are not because of large inductance (reactor) that is involved in their practice to generate dc input current. VSI has dc voltage input as its supply, while CSI has dc current as its source. The dc voltage electricity sources available such as batteries, solar panels or fuel cells are converted to dc current source by connecting in series a large inductance to establish current flow in the circuit. CSI can also be generated from a rectified ac voltage and filtering the ripples by a large reactor to produce dc input current \( I_d \) which flows into the inverter input and this value is independent of inverter load [1] as shown in Fig 1. Due to unavailability of feedback diodes, the CSI is short circuit proof. The only vivid demerit of this inverter topology is the weight of the reactor which increases the bulkiness of the inverter. Among other unidirectional switches that can be used in the design of this inverter include: (A) a Thyristor in which case there must be external commutation circuit, (B) Gate Turn Off thyristor (GTO) where positive current turns it ON or otherwise, (C) Transistors (BJT, MOSFET, IGBT) which cannot withstand high reverse voltage and therefore needs series diode.

The current source inverters have the following merits [2]:
- Since the input current is constant; misfiring of devices and short-circuits do not pose any problem.
- Peak current of devices is limited.
- Commutation circuit is simple.
- It can handle reactive or regenerative loads without freewheeling diodes.

![Fig. 1 A block diagram of a current source inverter from AC power source](image)

Some typical applications in which inverters may pay a pioneering role are variable speed ac drives, induction heating, stand-by power supplies, uninterruptible power supplies (UPS), traction, high voltage direct current transmission, static Var compensation and soon [3].

This paper presents a conventional single-phase full bridge current source inverter with load variation. This paper is structured as: In section I, the concept of current source inverter topology. Section II presents the circuit configuration and operational principles of the proposed inverter. In section III the novel pulse width modulation
technique is detailed and analyzed as well. Section IV, shows in details the MATLAB simulation results.

2. Configuration And Operational Principle Of The Proposed Inverter

2.1 Current source inverter leg configuration and operation

A current source inverter (CSI) in Fig. 2 does not usually have antiparallel diodes connected across the unidirectional switches because for a given switching state the active switch current flows in only one direction. In Fig. 2, the upper switch \( S_1 \) is turned ON and the lower switch \( S_4 \) turned OFF to allow the flow of positive inverter output current \( I_o \) which is equal to \( I_d \). In contrary, \( S_4 \) is turned ON and \( S_1 \) turned OFF to allow negative inverter output current \( I_o \) which is equal to \(-I_d\) to be drawn through the inverter output load. For zero current output (\( I_o \) equal to zero), \( S_1 \) and \( S_4 \) are simultaneously switched ON to short the constant input current \( I_d \) away from the output load. The constant source current \( I_d \) is usually obtained from a voltage source in series with a relatively large reactor (inductance) as shown in Fig. 1. The inverter Leg switching states are therefore summarized as shown in Table 1 below.

![Fig. 2 One Leg topology of conventional current source inverter.](image)

![Table 1. The switching states of the inverter Leg of Fig. 1.](chart)

<table>
<thead>
<tr>
<th>Mode</th>
<th>( S_1 )</th>
<th>( S_4 )</th>
<th>Output Current (( I_o ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ON</td>
<td>OFF</td>
<td>( I_d )</td>
</tr>
<tr>
<td>2</td>
<td>OFF</td>
<td>ON</td>
<td>(-I_d)</td>
</tr>
<tr>
<td>3</td>
<td>ON</td>
<td>ON</td>
<td>0</td>
</tr>
</tbody>
</table>

2.2 A conventional single-phase current source inverter with total load impedance is shown in Figure 3 below.

![Fig. 3: Configuration of the conventional single-phase current source inverter power circuit.](image)

The single phase current source inverter’s operation can be divided into four switching states, as shown in Table 2 and Fig. 4(a)-d. ON-state is depicted by 1 whereas OFF-state is depicted by 0.

![Table 2. Output current switching pattern.](chart)

<table>
<thead>
<tr>
<th>Modes</th>
<th>( S_1 )</th>
<th>( S_2 )</th>
<th>( S_3 )</th>
<th>( S_4 )</th>
<th>( I_a(A) )</th>
<th>( I_b(A) )</th>
<th>( I_o(A) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>( I_d )</td>
<td>0</td>
<td>( I_d )</td>
</tr>
<tr>
<td>( b )</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( c )</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>( I_d )</td>
<td>0</td>
<td>(-I_d)</td>
</tr>
<tr>
<td>( d )</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The required two levels of output current were generated follows.
1. **Mode (a) operation.**
When the switches $S_1$ and $S_2$ are turned ON, switches $S_3$ and $S_4$ are turned OFF, thus $I_d$ is allowed to flow through the load via the two ON switches. This flow permits positive current flow in the circuit. In Fig 4(a) above the thick darken line depicts current flow path in the circuit. Therefore, it is observed that inductor current, $I_d$ is equal to the load current, $I_o$.

2. **Mode (b) operation.**
When the switches $S_1$ and $S_4$ are turned ON, switches $S_2$ and $S_3$ are turned OFF, thus $I_d$ is not allowed to flow through the load. In this case, current source inverter is termed short circuit proof and therefore, the reactor is charged by the circuit current. In Fig 4(b) above the thick darken line depicts current flow path in the circuit. Therefore, it is observed that inductor current, $I_d$ is not equal to the load current, $I_o$ otherwise load current turns to zero.

3. **Mode (c) operation.**
When the switches $S_1$ and $S_2$ are turned OFF, switches $S_3$ and $S_4$ are turned ON, thus $I_d$ is allowed to flow through the load via the two ON switches. This flow permits negative current flow in the circuit. In Fig 4(c) above the thick darken line depicts current flow path in the circuit. Therefore, it is observed that inductor current, $I_d$ is equal to the negative load current, $I_o$ in the circuit.

4. **Mode (d) operation.**
When the switches $S_1$ and $S_3$ are turned OFF, switches $S_2$ and $S_4$ are turned ON, thus $I_d$ is not allowed to flow through the load. In this case, current source inverter is termed short circuit proof and therefore, the reactor is charged by the circuit current. In Fig 4(d) above the thick darken line depicts current flow path in the circuit. Therefore, it is observed that inductor current, $I_d$ is not equal to the load current, $I_o$ otherwise load current turns to zero.

3. **PULSE WIDTH MODULATION**

Pulse width modulation technique is now gradually taking over the inverter market due to its vital role in the control application. This is a method of controlling a targeted variable by switching action which shapes the voltage or current to take a waveform different from the condition at maximum variable value. The frequency of triangular waveform establishes the inverter switching frequency which is kept constant along with its amplitude [4]. In most applications, PWM in addition to varying instantaneous value of an output variable is carried out to reduce the harmonic content of the variable. Reduction of harmonic content helps to (i) reduce circuit losses and (ii) reduction of electromagnetic interference (EMI).

To achieve reduced harmonic content, many methods of modulation have been proposed. The most popular is the sinusoidal pulse width modulation technique where a reference sinusoid $V_r$ of amplitude $V_{rm}$ is used as modulation waveform to interact with a higher frequency carrier signal $V_c$ of amplitude $V_{cm}$ to generate the inverter switching signal. To generate output current or voltage with lesser harmonic contents, triangular waveform is always considered as the carrier signal.

A fundamental period in Fig. 5 consist of $N_r$ pulses whose widths vary sinusoidally throughout the cycle to give the fundamental component of frequency. One of these pulses, is characterized in detail in Fig. 6.
Fig. 5 Switching patterns of single phase current source inverter.

\[
\sin (A) = \sin (100\pi t) \quad (1a)
\]

If \( \sin(A) > 0 \); \( g_1 = 1 \); else \( g_1 = 0 \);
If \( V_{rm} < V_{cm} \); \( g_2 = 1 \); else \( g_2 = 0 \);
If \( \sin(A) < 0 \); \( g_3 = 1 \); else \( g_3 = 0 \);
If \( V_{rm} > V_{cm} \); \( g_4 = 1 \); else \( g_4 = 0 \);

(1b)

Where, \( f_c \) is the carrier or switching frequency and \( f_r \) is the reference/fundamental frequency.

In Fig. 6, the equation of first negative slope of section (A) of \( V_r \) is given by

\[
V_{cp1} = p\omega t + C \quad (3)
\]

Where, \( p \) is the slope and \( C \) is the intersection.

\[
C = V_{cm} \quad \text{and} \quad p = \frac{-V_{cm}N_r}{\pi}.
\]

\[
V_{cp1} = \frac{-V_{cm}N_r}{\pi} \omega t + V_{cm} \quad (4)
\]

when, \( \omega t = \alpha_2 \) then equation 4 must be equal to \( V_r \) which gives

\[
V_{rm} \sin \omega t = \frac{-V_{cm}N_r}{\pi} \alpha_2 + V_{cm} \quad (5)
\]

Dividing eqn. 5 by \( V_{cm} \) yields

\[
M \sin \omega t = \frac{-N_r}{\pi} \alpha_2 - 1 \quad (6)
\]

where, \( M \) is the modulation index and

\[
M = \frac{V_{rm}}{V_{cm}} \quad (7)
\]

The switching angular period \( \Delta \) and frequency modulation ratio \( N_r \) are respectively, given by

\[
\Delta = \frac{2\pi}{N_r} \quad (1c)
\]

\[
N_r = \frac{f_c}{f_r} \quad (2)
\]
The \( k \)-th sloped section (A) of \( \psi_c \) has \( v_{cm}, 3v_{cm}, 5v_{cm}, \ldots, (2k - 1)v_{cm} \).

Therefore, the intersection C is given by
\[
C = (2k - 1)v_{cm}
\]  
\( \text{(8)} \)

The general \( \alpha_k \) beginning of \( k \)-th pulse and is given by
\[
M \sin \alpha_k = \frac{-N_r}{\pi} \alpha_k + 2k - 1 < 0
\]  
\( \text{(10)} \)

In this same way, the \( k \)-th positive sloped section (B) of \( \psi_c \) has \(-v_{cm}, -3v_{cm}, -5v_{cm}, \ldots, -(2k - 1)v_{cm} \).

Therefore, the intersection C is given by
\[
C = (1 - 2k)v_{cm}
\]  
\( \text{(11)} \)

The general \( \beta_k \) in section (B) of Fig. 6 of positive slope beginning of \( k \)-th pulse and is given by
\[
M \sin \beta_k = \frac{-N_r}{\pi} \beta_k + 1 - 2k > 0
\]  
\( \text{(12)} \)

In equations (10) and (12), if \( M > 1 \), higher harmonics in the phase waveform are obtained. Therefore \( M \) is maintained between zero and one. If the amplitude of the reference signal is increased to be higher than the amplitude of the carrier signal, i.e. \( M > 1 \), this will lead to overmodulation.

Consequently, analyzing the harmonic spectra, two symmetrical pulses one positive and one negative is considered. The current harmonics generated by the sinusoidal PWM can be computed by first calculating the harmonics due to the \( k \)-th pulse alone, \( C_{nk} \), and then summing the harmonic contributions of all \( N_r \) pulses.

Fig. 7 Conventional current source inverter output current, \( I_{ok} \).

From Fig. 6 above,
\[
I_{ok} = \frac{v_{ok}}{Z}
\]  
\( \text{(13)} \)

where, \( Z \) is the load impedance and output voltage is given by
\[
v_{ok} = \sum_{n=1,3,5}\left[a_{nk}\cos n\omega t + b_{nk}\sin n\omega t\right]
\]  
\( \text{(14)} \)

Where \( a_{nk} \) and \( b_{nk} \) are the cosine and the sine amplitude of the \( n \)-th harmonic component.

\[
a_{nk} = \frac{1}{2\pi} \int_0^{2\pi} v_{ok}\cos n\omega t \, dt
\]  
\( \text{(16)} \)

Integrating equation (16) yields
\[
a_{nk} = \frac{2\pi a}{n\pi} \left( \sin n\beta_k - \sin n\alpha_k \right)
\]  
\( \text{(17)} \)

Similarly,
\[
b_{nk} = \frac{1}{2\pi} \int_0^{2\pi} v_{ok}\sin n\omega t \, dt
\]  
\( \text{(18)} \)

Integrating equation (18) yields
\[
b_{nk} = \frac{2\pi d}{n\pi} \left( \cos n\alpha_k - \cos n\beta_k \right)
\]  
\( \text{(19)} \)

Where the \( n \)-th harmonic amplitude of the \( k \)-th pulse pair is given by
\[
C_{nk} = \sqrt{a_{nk}^2 + b_{nk}^2}
\]  
\( \text{(20)} \)

Hence, the \( n \)-th harmonic amplitude of \( I_{o} \) made up of \( N_r/2 \) pulse pairs is given by
\[
C_n = \sum_{k=1}^{N_r/2} C_{nk}
\]  
\( \text{(21)} \)

Then, equation (21) can be expressed in terms \( I_d, \alpha_k \) and \( \beta_k \) by substituting equations (17), (19) and (20) into equation (21), which yields
\[
C_n = \frac{2\alpha d}{n\pi} \sum_{k=1}^{N_r/2} \left( \sqrt{1 + 2\cos n\beta_k \left( \cos n\beta_k - \cos n\alpha_k - \sin n\alpha_k \right)} \right)
\]  
\( \text{(22)} \)

Where, \( \alpha_k \) and \( \beta_k \) can be determined using equations (10) and (12) as \( M \) varies.

4. SIMULATION RESULTS UNDER DIFFERENT LOADS

Performance of the conventional single phase current source inverter has been studied with variations in loads. In order to validate the conventional inverter topology, simulations are carried out using MATLAB/SIMULINK software. The PWM switching patterns are generated by comparing one triangular carrier, \( v_c \) at switching frequency of 2kHz against a rectified sinusoidal reference wave, \( v_r \), a fundamental frequency of 50Hz, as shown in Fig. 4. It is assumed that the input current, \( I_d \) =25Amperes and reactor value, \( L_r \) = 2Henry. Other circuit parameters considered deliberately are \( R=8\)ohm, \( X_c = X_r = 60\)ohm and modulation index, \( M=0.8 \).

Subsequently, the comparing process produced PMW gating signals \( g_1 \ldots g_4 \) for the power switches \( S_1\ldots S_4 \). It is
observed that switch \( g_1 \) is complementary to switch \( g_3 \) and switch \( g_2 \) is complementary to switch \( g_4 \) as shown in Fig. 4. 

4.1 Resistive-Capacitive Load, 
\[
Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_C}\right)^2}}
\]

and \( \theta = \tan^{-1}\left(\frac{1}{X_C} \cdot \frac{1}{R}\right) \).

In the first case, parallel R-C load is appended across the inverter output to observe the response under harmonic components. Figures 7 and 8 reveal the response of SPWM controlled CSI with R-C load contains harmonic contents as shown in the figures below. In this case, current leads the voltage by the phase angle \( \theta \) consequently they contain THD of 59.62% and 31.64% respectively.

Fig. 7: Inverter Output Voltage Response with Parallel R-C Load

Fig. 8: Inverter Output Current Response with Parallel R-C Load

4.2 Resistive-Inductive Load, 
\[
Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L}\right)^2}} \quad \text{and} \quad \theta = \tan^{-1}\left(\frac{1}{X_L} \cdot \frac{1}{R}\right).
\]

Secondly, parallel R-L load is connected to the inverter output to observe the response under harmonic components. Figure 9 reveals high harmonic content in the output voltage waveform. Figure 10 shows a low output current value with higher harmonic content. Here, the outputs current and voltage are almost in phase with 59.49% and 59.86% THD contents respectively. The result depicts output current lower than input current.

Fig. 9: Inverter Output Voltage Response with Parallel R-L Load

Fig. 10: Inverter Output Current Response with Parallel R-L Load

4.3 Resistive-Inductive-Capacitive Load, 
\[
Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}} \quad \text{and} \quad \theta = \tan^{-1}\left(\frac{1}{X_L} \cdot \frac{1}{X_C} \cdot \frac{1}{R}\right).
\]

Afterwards, the implementation of parallel RLC load on the inverter ac terminals could trigger parallel resonance which shows current and voltage THDs of 59.61% and 30.22% respectively. Figures 11 and 12 show output voltage and current with their respective THD contents. It is observed that the output current is greater than input current. Furthermore, the output voltage is behind the output current by a value of phase angle \( \theta \).
4.4 Inductive-Capacitive Load, \( \theta = \tan^{-1}\left(\frac{1}{X_L} - \frac{1}{X_C}\right) \) and \( Z = \frac{1}{\frac{1}{X_L} - \frac{1}{X_C}} \).

Finally, parallel L-C load is appended across the inverter output to observe the response under harmonic components. Figures 13 and 14 reveal the response of SPWM controlled CSI with L-C load contains harmonic contents as shown in the figures below. In this case, current leads the voltage by the phase angle \( \theta = 90^\circ \) while the output current THD shows of 24.80% and output voltage is 59.69%. This load connection shows that the output current is greater than the input current value with improved output voltage amplitude.

5. CONCLUSION

Conventional single phase current source inverter offer improved output voltages and current waveform with higher THD. This paper has presented a novel rectified sine-triangular wave pulse width modulation switching scheme for the conventional single phase full bridge current source inverter topology. It utilizes a rectified reference signal and a triangular carrier signal to generate PWM switching signals for the power semiconductors. The current source inverter topology can be used for different industrial and home application due to its voltage and current responses under different load variations. The behavior determined with variable load on the inverter ac terminals is observed under a constant modulation index of 0.8 and frequency modulation index of 40.

REFERENCES


[6] Jeyraj Selvaraj and Nasrudin A Rahim’ Multilevel inverter For Grid connected PV System Employing Digital PI Controller’ IEEE transactions on
BIBLIOGRAPHY OF AUTHORS

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